Crab pulsar optical photometry with microsecond temporal resolution

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Abstract

The fine structure and the variations of the optical pulse shape and phase of the Crab pulsar is studied on various time scales. The upper limit on the pulsar precession on Dec 2, 1999 is placed in the 10 s - 2 hours time range. The evidence of a varying from year to year fine structure of the main pulse peak is found in the 1999 and 2003 years data. No such fine structure is detected in the integral pulse shape of 1994, 1999 and 2003 years.
The drastic change of the pulse shape in the 2005-2006 years set is detected along with the pulse shape variability and quasi-periodic phase shifts.

Table 1: Log of observations

Date	Telescope	Duration, sec	Spectral range
Dec 7, 1994	BTA[1], Russia	2400	U+B+V+R
Dec 2, 1999	WHT[2], Canary	6600	R
Nov 15, 2003	BTA[2], Russia	1800	R
Dec 29, 2005 - Jan 3, 2006	BTA[3], Russia	48000	4000 - 7000 A

[1] Four-colour photometer with photomultiplier
[2] Avalanche photo-diode
[3] Panoramic spectro-polarimeter with position-sensitive detector

Observations

We analyzed the sample of observational data obtained by our group over the time span of 12 years on different telescopes. The details of observations are summarized in Table 1. The equipment used were four-color standard photometer with diaphragms based on photomultipliers, fast photometer with avalanche photo-diodes[1] and panoramic spectro-polarimeter based on position-sensitive detector[4, 5]. All devices provide the $1\mu s$ time resolution.
For each data set the list of photon arrival times has been formed. They have been processed in the same way by using the same software to exclude the systematic differences due to data analysis inconsistencies.
Photon arrival times have been corrected to the barycenter of the Solar System using the adapted version of *axBary* code. The accuracy of this code has been tested with detailed examples provided by [2] and is found to be better than $2\mu s$.
The barycentered photon lists then have been folded using both Jodrell-Bank radio ephemerides[3] and our own fast-folding based method of timing model fitting.
The accuracy of timing model is proved to be better than at least several microseconds (see Figure 1), which permits to fold the light curve with 5000 bin (6.6 us) resolution.

Phase stability

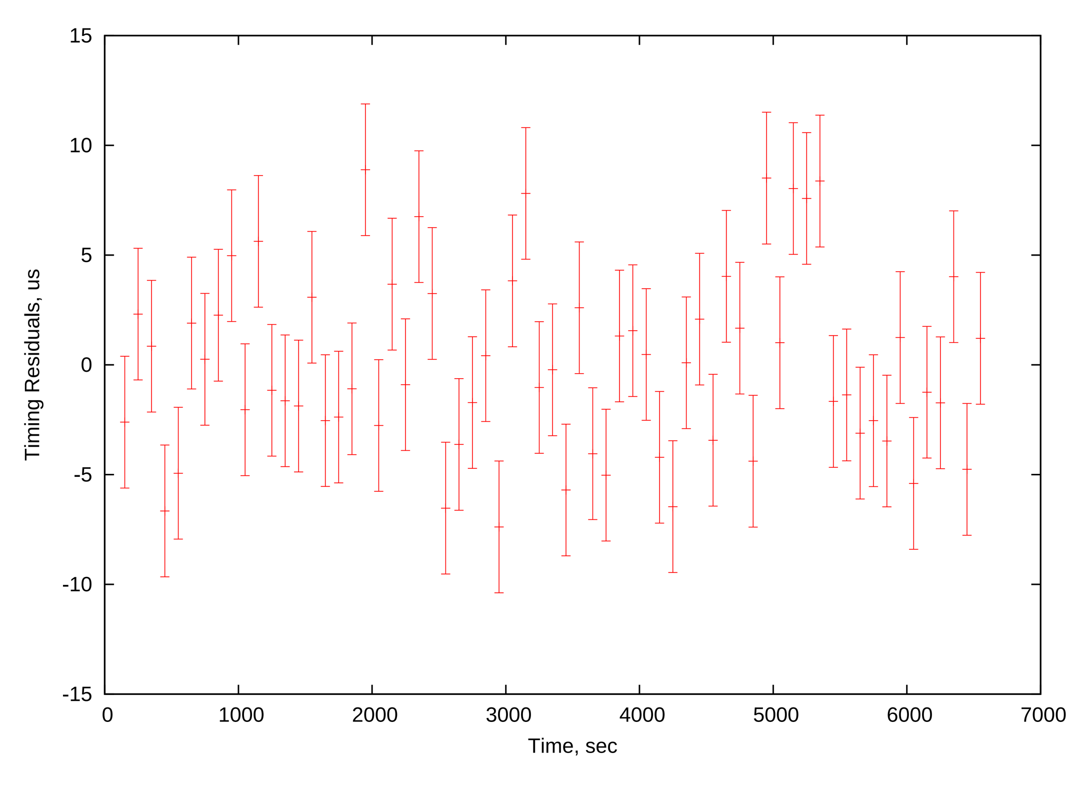

Figure 1: Timing residuals of the Crab pulsar after applying second-order timing model (up to second frequency derivative) to data of 1999 year. It corresponds to the Gaussian noise with 4.1 us rms.

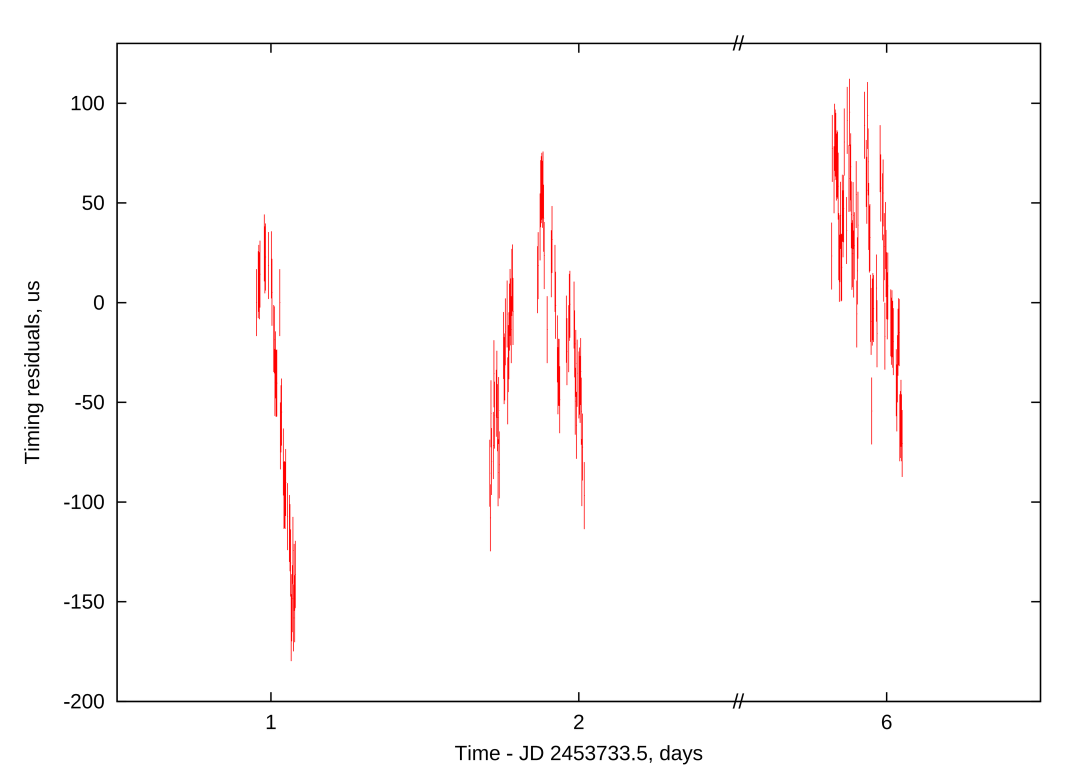

Figure 2: Timing residuals of the Crab pulsar after applying second-order timing model to data of 2005-2006 year. The quasi-periodic behaviour with characteristic time scale of 0.7 days is seen.

We performed the search for timing model residuals using two longest continuous data sets of 1999 and 2005-2006 years. The data has been divided into the number of subsets of fixed length and they have been folded separately using the same base epoch. Then the sample light curves have been cross-correlated with the standard one (which has been derived for each set separately by folding the whole data) and its phase shift have been derived by fitting the maximum of the cross-correlation function with the Gaussian. The results for 1999 year set are shown in Figure 1. No evidence for significant deviations from zero is seen, the phase is consistent with the Gaussian noise with $4.1\mu s$ rms in the 10 s - 2 hr time range.
The data of the last set of 2005-2006 years, however, show the significant quasi-periodic variations with $\sim 2.5 \cdot 10^{-3} P$ rms amplitude. The characteristic time scale of the variations is estimated to be roughly 0.7 day.

Pulse shape

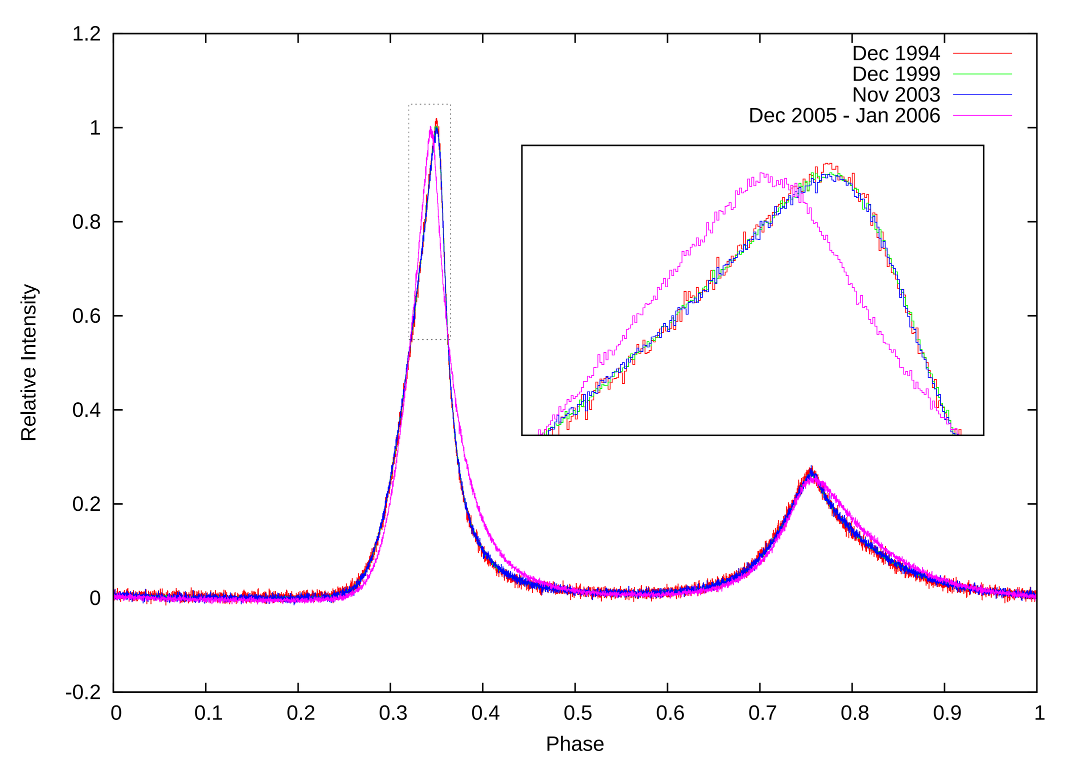

Figure 3: Phased light curves of the Crab pulsar for all observations sets, scaled to the same pulse height.

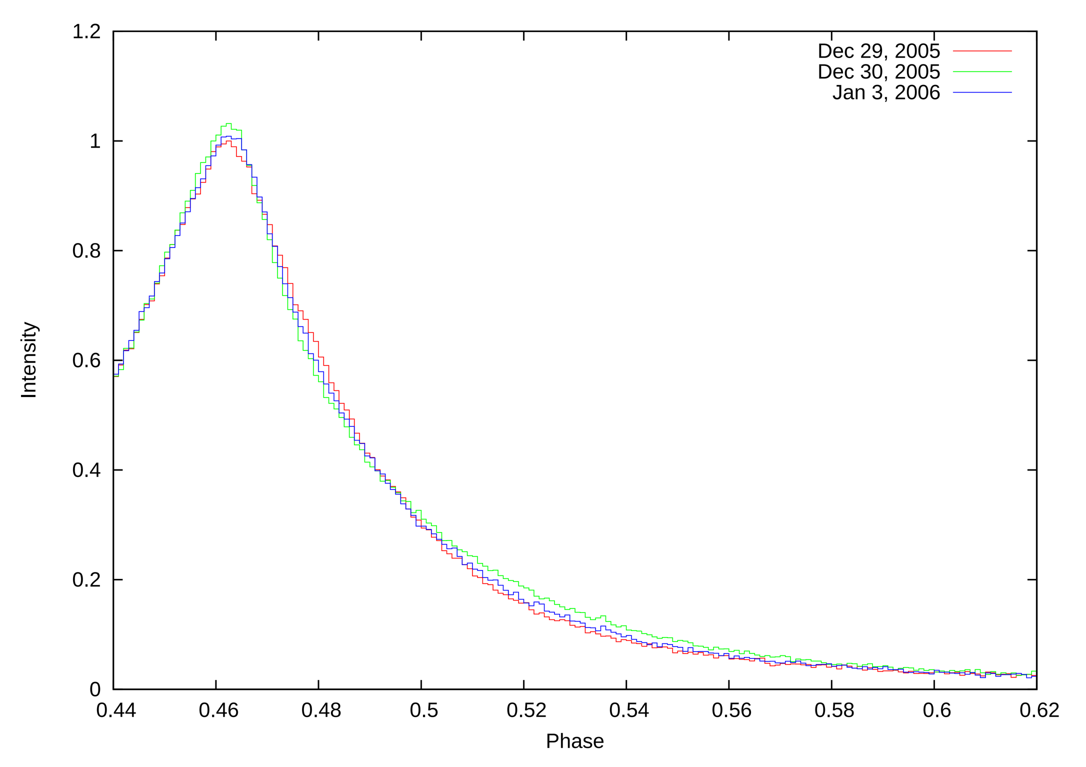

Figure 4: Phased light curves of the Crab pulsar for the three nights of the Dec 2005 - Jan 2006 set.

Due to the presence of significant residuals relative to the timing model the pulse profile during the observations of 2005-2006 years can't be derived by folding the whole data set directly. Instead, we divided the data set into the one-hour segments and folded them separately applying the time shift corrections to compensate the phase residuals. The intrinsic phase shift inside each block is less than $2 \cdot 10^{-4}$, so the folding with 5000 bins is possible. The folded light curves have been co-added.
All the other data has been folded directly and shifted in phase to the same pulse position for the ease of comparison. All pulse profiles are shown in Figure 3, with the off-pulse emission subtracted and pulse height scaled to the same value.
The profiles of 1994, 1999 and 2003 years are in a perfect agreement with each other. The profile of 2005-2006 years, however, deviates from them significantly – the pulse remains of the same FWHM while its skewness is much smaller, and its shape is nearly symmetric.
We folded the data of this set for each of three observational nights separately using the same method. These profiles are shown in Figure 4. There is the significant variation of its shape from night to night. Unfortunately the low amount of data available do not permit to track the profile shape change inside each night and check whether it is smooth or whether the shape is correlated with the timing residuals.

Main pulse peak fine structure

For the first three observational set where the pulse profile is stable we performed the search for the fine structure of the main pulse peak. The data sets has been reduced to the same phase base point with precision better than half of the phase bin (less than $3.3\mu s$) and the cumulative light curve has been computed. The peak region of it is shown on Figure 5. No statistically significant deviations from the smooth peak shape is seen. However, light curves of 1999 and 2003 years data sets alone (plotted on Figure 6) each show the evidence of fine structure on the level of 3-5 sigma (roughly 1 % of the intensity) with typical duration of 10-30 us. Such details may give an evidence of coherent generation of optical emission, if the emission generation region is deep enough (deeper than 0.1 of light cylinder radius), due to brightness temperature exceedes 10^{12} K.

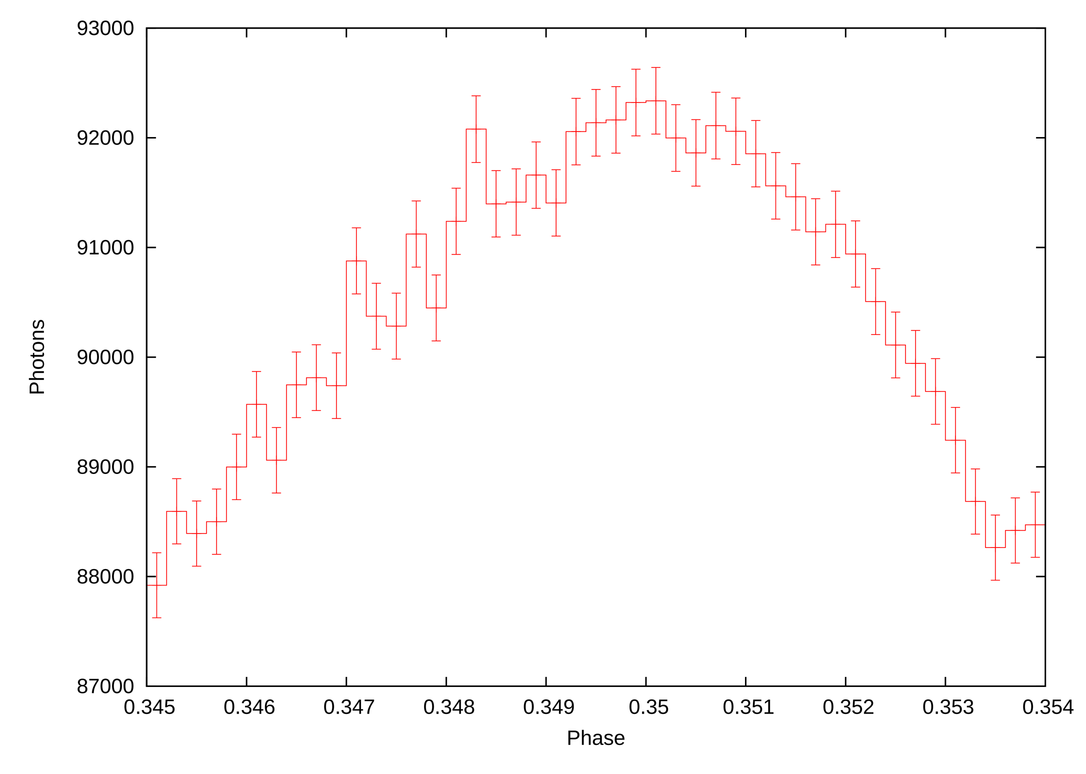

Figure 5: The main pulse peak of the sum of light curves of 1994, 1999 and 2003 years data.

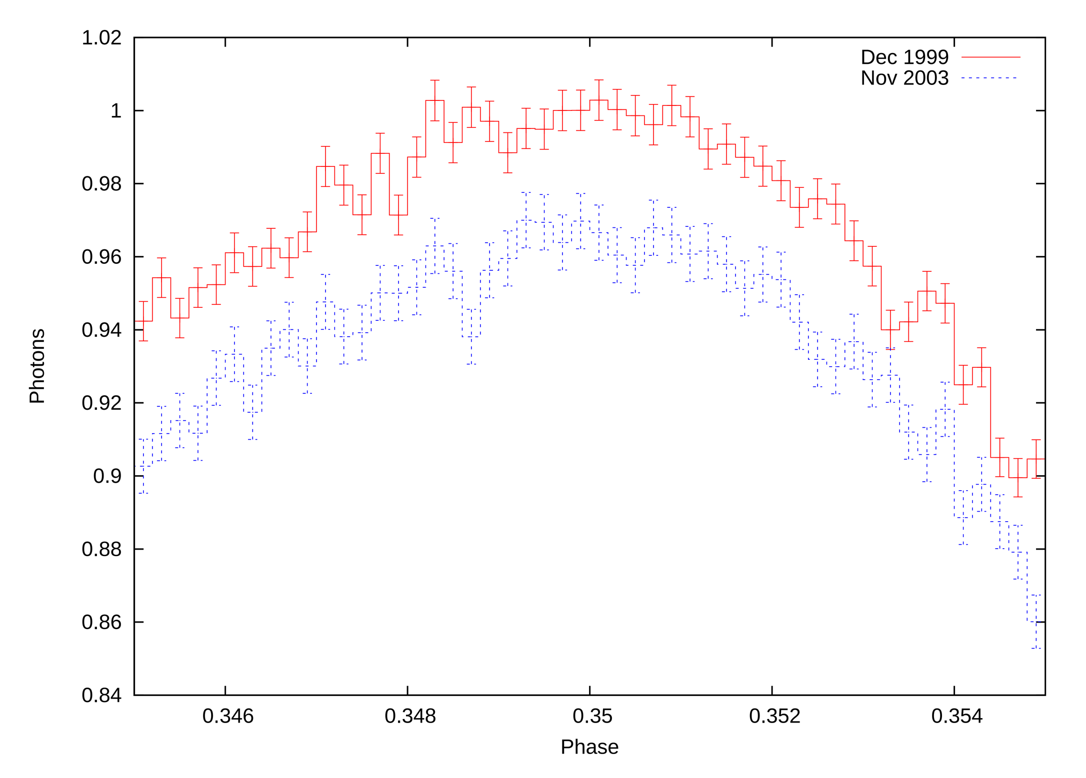

Figure 6: The comparison of the peaks of 1999 and 2003 years. The peaks are shifted vertically for 0.03 for clearance.

Conclusions

We analyzed the data of several sets of optical observations with high temporal resolution of the Crab pulsar performed by our group over the 12 last years. We found that the pulse profile has been very stable on the 1994 - 2003 years interval.
No evidence for short time scale precession (like 60-sec free precession discovered in [6]) is detected on the level of 10^{-5} - 10^{-7} s^{-1} pulsar frequency variation on 10 s - 2 hours time scale on Dec 2, 1999 (see Figure 1), which corresponds to the precession wobble angle to be less than approximately $2 \cdot 10^{-3}$. Also, no signatures of short time scale timing noise is seen in this data set.
No significant fine structure is detected in the integral pulse profile of 1994, 1999 and 2003 years data set (see Figure 5), however, each data set alone show the evidence of fine structure on the level of 3-5 sigma, which may be related to its instability on the time scale of years along with the stability of the pulse shape on the same scale.
We discovered the significant change of the time-averaged Crab pulse profile in the Dec 2005 - Jan 2006 set of observations. The pulse profile also shows the variations between the nights. Also, the quasi-periodic phase shifts in respect to the second-order timing solution (up to second frequency derivative) has been detected in the data with amplitude of $\sim 100\mu s$ and characteristic time scale of 0.7 days. We have not found any hardware or software issue able to mimic such pulsar behaviour. These results may be interpreted as a geometric effects due to the Crab precession suddenly started between our observations of 2003 and 2005-2006 years.

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References

[1] Shearer, A., et al.: Enhanced Optical Emission During Crab Giant Radio Pulses. Science, **301**, 493-495 (2003)

[2] Lyne, A.G., Jordan, C.A. & Roberts, M.E.: Crab Monthly Ephemeris available on http://www.jb.man.ac.uk/ pulsar/crab.html (2005)

[3] Jordan, C.A.: Private communication. (2006)

[4] V. Debur, et al.: The Position-Sensitive Detector for the 6-meter optical telescope. Nuclear Instruments and Methods in Physics Research. **A 513**, 127-131. (2003)

[5] Plokhotnichenko V., et al.: The Multicolor Panoramic Photometer-Polarimeter with high time resolution based on the PSD. Nuclear Instruments and Methods in Physics Research. **A 513**, 167-171. (2003)

[6] Cadez, A., et al.: Crab pulsar photometry and the signature of free precession. A&A, **366**, 930-934 (2001)